A Compact LTCC Ku-Band Transmitter Module with Integrated Filter for Satellite Communication Applications

C.-H. Lee, A. Sutono, S. Han*, and J. Laskar

Packaging Research Center, School of ECE, Georgia Institute of Technology

Yamacraw Design Center, Atlanta, GA 30332; Email address: gt2260b@prism.gatech.edu

* Currently with RF Solutions, Atlanta GA 30332

***Abstract* — We present the first demonstration of an ultra compact low temperature co-fired ceramic (LTCC) based transmitter module using commercial GaAs MESFET MMICs for Ku-band satellite communication applications. The upconverter MMIC integrated with a VCO exhibits a measured up-conversion gain of 9 dB and an IIP3 of 17 dBm, while the power amplifier (PA) MMIC shows a measured total gain of 31 dB and a 1-dB compression output power of 26.5 dBm at 14 GHz. Both MMICs were integrated on a compact LTCC module where an integrated front-end band pass filter (BPF) with a measured insertion loss of 1.8 dB at 14.5 GHz was integrated. This transmitter module has a compact size of 400 × 310 × 35.2 mil^3.**

I. INTRODUCTION

To satisfy the significant worldwide demand for higher data rates and broadband transmission, applications of satellite communication systems in the Ku/Ka-band range are expanding due to its large available bandwidth [1]. However, there is still a deficiency of economical high-frequency components for low-cost home transceivers. The current drawbacks of most commercially available transceivers are their relatively large size, heavy weight, and separately located modules [2]. The implementation of a compact transmitter module is a key issue for reduction in cost, size and system complexity. One obstacle for a compact transceiver module is the large and heavy cavity filter that cannot be easily integrated into the module [2][3]. In this paper, we present for the first time a functional compact LTCC-based transmitter module featuring an integrated filter and MMIC chipsets utilizing a low-cost commercial TriQuint's TQTRX 0.6 μm GaAs MESFET process with a f_t of 20 GHz. Most of the LTCC-based modules demonstrated so far [4]-[6] were dedicated for phased-array applications. The feasibility of implementing a LTCC integrated filter has been demonstrated in [7]-[8] for L-band application. The same concept is now extended for Ku-band applications. We show that a functional low cost Ku-band satellite module can be implemented using commercial GaAs and LTCC processes despite some major challenges, considering the design frequency is very close to the f_t of the device technology as well as the loss and bandwidth requirement of the filter.

II. MMIC DESIGN AND PERFORMANCE

System level studies have been performed to obtain the transmitter specifications such as output power level and linearity, as well as the filter requirement by utilizing the Agilent ADS system simulator. The transmitter module incorporated an integrated BPF and two MMICs; an upconverter MMIC and a PA MMIC. The upconverter MMIC consists of a dual-gate mixer, a low phase noise voltage controlled oscillator (VCO), a local oscillator (LO) buffer amplifier and a RF amplifier while the PA MMIC consists of a driver amplifier and a PA. This configuration was selected to apply the filtering network between two MMICs and to avoid the thermal effect on the upconverter MMIC as shown in Fig. 1.

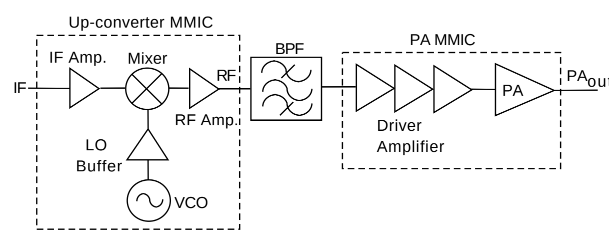

Fig. 1. Transmitter block diagram.

The upconverter MMIC was implemented with a dual-gate mixer in the unbalanced configuration operating over the 14 GHz to 14.5 GHz band. The dual gate topology provides simplicity, lower distortion, and good LO-IF isolation [9]. Having conversion gain eliminates the need for additional gain stages to compensate for the loss. Good LO to RF isolation and image signal rejection has been achieved through the use of a LTCC BPF at the RF port. The dual gate transistor is modeled as two single gate transistors in series. The LO signal is generated by an integrated MMIC VCO. The common-gate configuration was used to generate strong negative resistance by inductive feedback. Although a much wider tuning bandwidth can be obtained by placing the varactor on the gate path, the varactor was incorporated on the source path in the resonator to reduce its noise contribution to the VCO. In addition, the reflection coefficient line analysis was performed to achieve low phase noise performance [10]. To eliminate undesirable low frequency oscillations, an LC network is also incorporated as a high pass filter on the output path. The LO buffer amplifier was designed to deliver the required drive power (about 15 dBm) to the mixer and to facilitate better output matching in addition to desensitizing the VCO to the external load impedance. It uses a conventional single-stage common-source amplifier topology incorporating reactive matching. The measured conversion gain and IIP3 of the dual-gate mixer at the output RF frequency (14 GHz) are 2 dB and 17 dBm, respectively, at a LO power of 15 dBm, as shown in Fig. 2. The RF amplifier with 7 dB gain was designed to increase the conversion gain of the entire upconverter MMIC. The mixer demonstrates flat conversion gain performance across IF frequencies between 0.7 GHz to 1.5 GHz.

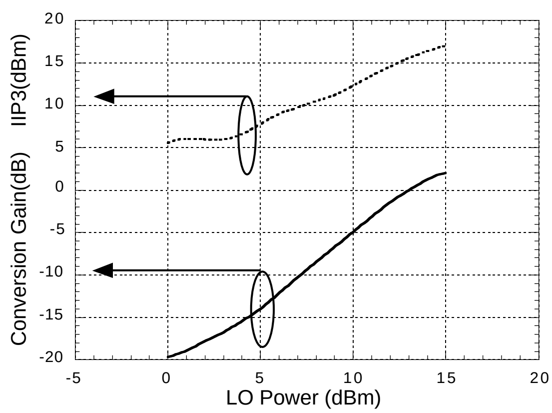

Fig. 2. Measured conversion gain and IIP3 of mixer.

The measured LO to IF isolation of better than 20 dB and LO to RF isolation of 10 dB was obtained over the entire band. Due to the high pass network at the mixer output, measured RF to IF isolation of much better than 30 dB can be achieved.

A negative resistance VCO was implemented showing a measured phase noise of –85 dBc/Hz at a 100 KHz offset as shown in Fig. 3. A second harmonic suppression of 20 dB or more was observed across the entire power and frequency range, and no parasitic oscillations were detected. A maximum output power of 10.5 dBm was measured and a power control level of 12 dB was obtained by varying the drain voltage from 1.5 to 4 V. A frequency tuning range of 600 MHz, ranging from 12.6 GHz to 13.2 GHz, with uniform phase noise performance was achieved over a tuning voltage range of –1 to +3 V. These characteristics have been achieved without any buffer amplifiers. The LO buffer amplifier provides 7 dB gain at 13 GHz, and has an input 1-dB compression point of 18 dBm.

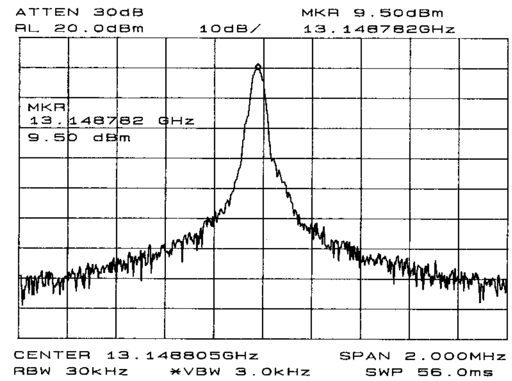

Fig. 3. Output frequency spectrum of the VCO over a 2MHz span.

From the PA MMIC, an output power of 26.5 dBm was achieved over a 500 MHz RF bandwidth. In order to meet the output power specification, the five-stage driver amplifier was designed to produce more than 25 dB of gain from 14 GHz to 14.5 GHz. The amplifier was realized with five-stage 500 µm FETs using the reactive matching as well as feedback resistance for unconditional stability. The common-source topology and single bias supply scheme is used to simplify the biasing circuitry. The resulting amplifier exhibited measured gain of 26 dB and return loss of better than 15 dB over the entire frequency band while drawing 300 mA from 4 V supply. Measurement shows that its 1-dB compression point is 23 dBm across the required frequency range. A class-A power amplifier was designed using a nonlinear large signal model (TOM3) and the dynamic load line method. To meet the design goals, a 1.5 mm device was selected for single-ended one-stage common source amplifier design.

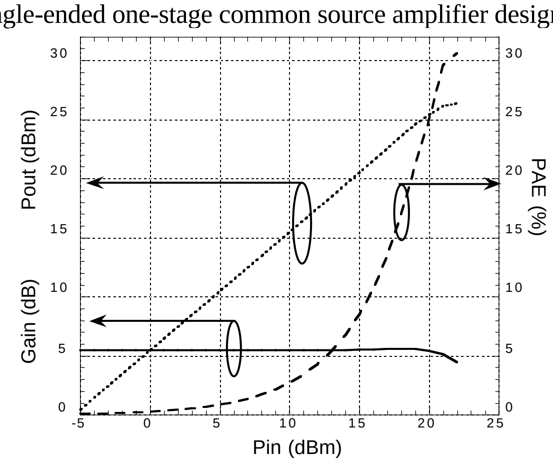

Fig. 4. Gain, output power, and PAE performance of the PA.

The PA area is 26 × 63 mil^2 and incorporates all dc blocking and bypassing capacitors on-chip. The PA operates at 5 V with 200 mA drain current. Lumped elements were used to realize the matching network. The PA exhibits about 5 dB gain with a 1-dB compression point of 26.5 dBm and a PAE of 30 % as shown in Fig. 4. A return loss of better than 12 dB was observed over the desired frequency band. For an accurate inductor model, a commercial method of moments (MoM) simulator [10] was utilized and the distributed effects of metal interconnects in the layout were considered. This MMIC also includes pads for on-wafer testing and shunt capacitors on the bias pads to minimize parasitic effects of the dc probes.

III. LTCC Transmitter Module

The two MMICs have been integrated on a multi-layer LTCC substrate where a stripline front-end transmitter filter was integrated. The LTCC material where the 8 stacked layer module was built is the recently introduced Dupont 943AT, fabricated by National Semiconductor Corporation. Each tape layer has a thickness of 4.4 mils with 7μm gold or silver paste metalization. Fig. 5 depicts the three-dimensional view of the LTCC module where the MMIC chips were wire-bonded on the surface. The stripline filter was designed using three coupled-line segments where the middle segment was deployed perpendicular to the first and third segments for compactness as illustrated in the footprints in the middle layer. This is a balanced stripline topology where the coupled-line segments are sandwiched by two ground planes at an equal distance of 17.6 mils (four tape layers) as indicated in Fig. 5.

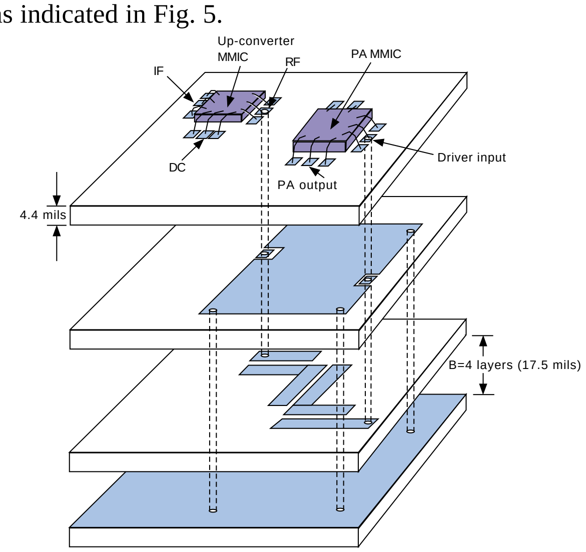

Fig. 5. Exploded view of transmitter MCM module with LTCC integrated filter.

The length of the wirebond is approximately 40 mil. The estimated loss of 40 mil ball crescent bond wires incorporated in the module at 14 GHz is 2 dB [12]. The filter ground planes were properly connected to the ground pads on the surface layers wire-bonded to the ground pads on the MMICs. Also shown in Fig. 5, the filter input was transitioned to the CPW line wire-bonded to the RF port of the mixer while the output transition to CPW was wire-bonded to the input of the driver amplifier. Such configuration where the filter is integrated between the mixer and PA was chosen to eliminate the mixer harmonics and thereby, improving the linearity of the transmitter. The transition to CPW also enables separate measurement of the filter whose measured return and insertion losses are plotted in Fig. 6. This filter exhibits a maximum insertion loss of 1.8 dB from 13.5 to 14.5 GHz with the corresponding return loss as high as 20 dB at 14.5 GHz. We measured all the components in the transmitter module and get the link budget. The implemented LTCC-based transmitter module occupies a compact area of 400 × 310 × 35.2 mil^3 as shown in Fig. 7.

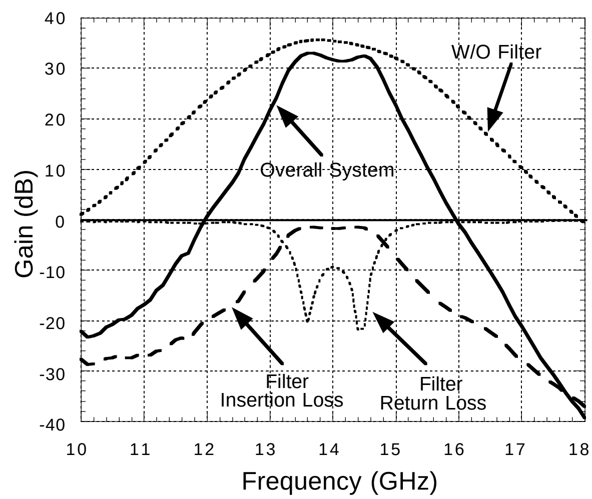

Fig. 6. Overall system gain performance with filter characteristics.

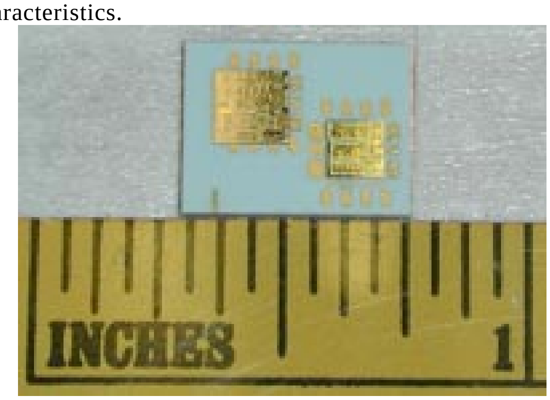

Fig.7. Photograph of the fabricated LTCC transmitter module.

The entire transmitter chain exhibits a total gain of 32 dB incorporating the wirebond loss from 13.5 GHz to 14.5 GHz and image rejection of more than 30 dBc at 12 GHz as shown in Fig. 6.

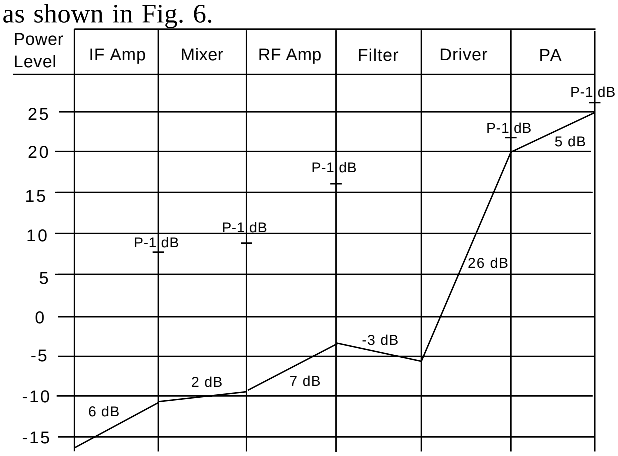

Fig. 8. Level diagram of the entire transmitter system with 1-dB compression point.

Fig. 8 shows the overall system level diagram of the entire transmitter chain based on the measurement of each transmitter block. Measurements were made on-wafer using a coplanar probe station, a network analyzer and a spectrum analyzer. The transmitter exhibits an output power of approximately 26 dBm incorporating the losses and mismatches caused by the bond wires and the filter.

IV. CONCLUSION

We have presented the first demonstration of a compact LTCC-based transmitter module with functional MMICs consisting of VCO-mixer and PA implemented in a commercial GaAs MESFET technology. The upconverter MMIC demonstrated the conversion gain of 9 dB and IIP3 of 17 dBm. The PA MMIC exhibits the total gain of 31 dB and 1-dB compressed output power of 26.5 dBm. The compact module was made possible by embedding the filter and thereby saving more than 40 % of real estate compared to if it were implemented on a typical alumina substrate. The integrated stripline filter inserted between the mixer and the PA demonstrates low insertion loss of 1.8 dB and wide band performance of more than 500 MHz. The transmitter module exhibits a total gain of 32 dB and output power of 25 dBm incorporating wirebond and filter loss. This ultra compact module is an attractive solution for low-cost Ku-band satellite communication applications, especially for outdoor units.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support of the NSF Packaging Research Center at Georgia Tech under contract ECE-9402723 as well as the Yamacraw Design Center. We also would like to thank Ray Brown and Mike Ehlert from National Semiconductor for fabricating the LTCC prototypes, as well as TriQuint Semiconductor for MMIC fabrication.

REFERENCES

[1] J.V. Evans, "Proposed U.S. Global satellite systems operating at Ka-Band," *IEEE Aerospace Conference*, vol. 4, pp. 525-537, 1998.

[2] Ge Zhiqiang, "A downsized and integrated C-band transceiver for VSAT," *1995 IEEE Microwave and Optoelectronics Conference*, vol. 1, pp. 33-36, 1995.

[3] J. B. Shealy, etc, "A 2 Watt Ku-band Linear Transmit Module for VSAT Applications," *1999 IEEE MTT-S Digest*, vol. 2, pp. 1055-1058, Anaheim, CA.

[4] W. Simon, R. Kulke; A. Wien, M. Rittweger, L. Wolff, A. Girard, and J.-P. Bertinet, "Interconnects and transitions in multilayer LTCC multichip modules for 24 GHz ISM-band applications," *2000 IEEE IMS Digest*, vol.2, pp. 1047-1050, Boston, MA.

[5] K. Fujii, Y. Hara, Y. Shibuya, T. Sakai, and Y. Takano, "Highly integrated T/R module for active phased array antennas," *1998 IEEE RFIC Digest*, pp. 77-80, Baltimore, MD.

[6] J.W. Gipprich, L.E. Dickens, J.A. Faulkner, "Power amplifier yields 10 watts over 8-14 GHz using GaAs MMICs in an LTCC serial combiner/divider network," *1993 IEEE IMS Digest*, vol. 3 pp. 1369-1372, Atlanta, GA.

[7] A. Sutono, J. Laskar, and W.R. Smith, "Development of three dimensional integrated bluetooth image reject filter,"*IEEE-IMS Digest*, vol.1, pp. 339-342, Boston, MA, June 2000.

[8] J.A. Lester, M. Ahmadi, S. Peratoner, J. Hathaway, D. Garske, P.D. Chow, "Low cost miniaturized EHF SATCOM transceiver featuring HEMT MMICs and LTCC multilayer packaging," *IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium Digest*, pp. 35–38, 1995.

[9] C. Tsironis, R. meierer, and R. Stahlmann, "Dual-Gate MESFET Mixrs," *IEEE Trans. on Microwave Theory and Techniques*, vol. 32, no. 3, pp. 248-255, March 1984.

[10] C.-H. Lee, S. Han, B. Matinpour, and J. Laskar, "A low phase noise X-band MMIC GaAs MESFET VCO," *IEEE Microwave and Guided Wave Letters*, vol. 10, no. 8, pp. 325-327, August 2000.

[11] EM Users Manual, Sonnet Software Inc., Liverpool, NY.

[12] A. Sutono, N.G. Cafaro, J. Laskar, E.M. Tentzeris, "Experimental study and modeling of bond wire interconnects for microwave integrated circuits," *IEEE AP-S*, vol. 4, pp. 2020-2023, Salt Lake City, UT, January 2000.